water

MDPI

Article

Spatiotemporal Dynamics of Water Table Depth Associated with Changing Agricultural Land Use in an Arid Zone Oasis

Mireguli Ainiwaer [1,2], Jianli Ding [1,2,*], Jingjie Wang [1,2] and Nasiman Nasierding [1,2]

1 College of Resources and Environmental Science, Xinjiang University, Urumqi 830046, China; mihray_1221@sina.com (M.A.); skytian552@sohu.com (J.W.); nasima_422@163.com (N.N.)
2 Ministry of Education Key Laboratory of Oasis Ecology, Xinjiang University, Urumqi 830046, China
* Correspondence: watarid@xju.edu.cn; Tel.: +86-135-7926-5967

Received: 4 January 2019; Accepted: 25 March 2019; Published: 1 April 2019

Abstract: Investigating spatiotemporal dynamics and varying relationships between water table depth (WTD) and land use changes is critical for efficient groundwater management and land use planning in arid zones. The primary objective of the present study is to combine satellite and field measured data to quantitatively analyze variations in WTD and its relationship with land use change in the Ogan–Kucha River Oasis in the northwest arid zones of China, and reveal the spatial heterogeneity and variations in the abovementioned relationship at spatiotemporal scales. The spatiotemporal variations in WTD and land use change at different time intervals (1997–2007, 2007–2017, and 1997–2017) were analyzed based on geostatistical analysis methods and grid cell approaches. The relationships between land use types and changes in WTD were assessed using correlation and ordinary least square analyses. The relationships between spatiotemporal variations in WTD and land use change were explored using local level geographically weighted regression. The results indicated that influences of human activity on the variation of WTD have gradually increased, and that WTD has declined rapidly in most parts of the study area. The spatial distribution of WTD exhibited significant spatiotemporal heterogeneity, and WTD was lower in the inner parts of the oasis and shallower in the oasis-desert ecotone. The WTD decline rates in the irrigation area were much higher than those in the oasis-desert ecotone. The cultivated land area has expanded markedly, whereas the shrub covered area has shrunk rapidly. Changes in WTD were positively correlated with changes in cultivated land area, and the expansion center of cultivated land has gradually moved from upstream of the alluvial fan to downstream of the alluvial fan and to the oasis-desert ecotone. The relationships between changes in cultivated land and WTD in the ecotone were more prominent than those in the inner parts of the oasis. Therefore, agricultural land expansion and planning in the study area should be integrated based on spatiotemporal changes in the groundwater depth to maintain the stability of groundwater systems and sustainable groundwater exploitation.

Keywords: land use change; water table depth; spatiotemporal relationship; geographical regression analysis; arid zone oasis

1. Introduction

Groundwater is one of the most valuable and vulnerable freshwater resources [1], which plays a critical role in irrigated agriculture and global food security [2]. In addition, groundwater serves as the primary source of drinking water in both rural and urban areas, providing fresh water storage for domestic, agricultural, and industrial demands, while meeting basic human needs and maintaining the ecological balance and aquatic ecosystems [3–5]. In arid and semi-arid regions that have naturally existing desert oasis with limited surface water storage, groundwater becomes the major lifeline, supplying freshwater for rivers, wetlands and vegetation [6,7]. Particularly during droughts, groundwater storage acts as a natural buffer against water shortages, maintaining base-flows to rivers and wetlands and providing vital support for natural ecosystems. However, most arid regions have focused on achieving rapid economic growth, which has resulted in an ever- increasing food demand and overexploited groundwater resources, with less importance on maintaining a balance between the supply and demand for groundwater resources. In addition, groundwater discharge rates have exceeded the natural recharge rates, whereas withdrawal intensities have reached the highest levels, resulting in successive depletion of water table depth (WTD) and deterioration of water quality [8–11]. Groundwater states are closely linked to landscape status and activities; therefore, they are very sensitive and vulnerable to anthropogenic activities [12]. Land use land cover (LULC) change is a major form of human activity. LULC considerably impacts groundwater by modifying hydrological process, runoff mechanisms, and groundwater systems at spatial and temporal scales [13–15]. Various mechanisms of LULC change determine groundwater recharge rates and influence the quality and quantity of groundwater. In addition, LULC change activities have long-term and irreversible impacts on aquifers; they also alter the natural cycles and replenishment modes of groundwater system.

Previous studies have mostly applied conventional statistical methods, such as the ordinary least square (OLS) method, to examine the relationships between WTD and land use change. These conventional statistical methods are global-level statistical tools [16–20] that mostly rely on the assumptions of no autocorrelation and homoscedasticity and consider the relationship between WTD and LULC change as constant over space, thereby resulting in average or global level parameter estimates [21–24]. However, groundwater resources and land use types are strongly influenced by various environmental and human factors, and the relationship between WTD and LULC change is not constant over spaces, rather it significantly varies over space. Conventional estimation methods for establishing the relationship between WTD and LULC change may be inappropriate because the relationships between WTD and LULC change could be positively correlated in some parts of the study areas and negatively correlated or have no correlation in other parts [25–27]. To address such non-stationary problems, British geographer Brunsdon et al. proposed a novel method of integrating spatial correlation into the regression model in the form of geographically weighted regression (GWR) analysis. The GWR model, an extension of the traditional regression framework, explicitly incorporates spatial locations of data and explores non-stationarity and spatial variation for continuous surface parameter values at regional scales [28,29]. As a powerful geographic tool, the GWR model first appeared in the field of human geography, and has gradually found applications in the fields of economics, ecology, environmental science, and meteorology [30–34]. Although the model has been applied in numerous fields, thus far, it has only a few applications in the examination of the relationship between LULC and WTD changes. When GWR was first applied to examine the relationship between WTD and LULC changes, the results demonstrated that compared with traditional linear regression models, GWR could consider information neglected by OLS models and enhance the predictive ability of the model [35]. Therefore, GWR could be a useful tool for exploring the relationship between groundwater and land use change in addition to its spatial variation.

Since China initiated reforms and adopted an open door policy, rapid LULC change has occurred across the nation. Owing to the unequal levels of socio-economic and agricultural development, a disparity exists between the developed eastern regions and undeveloped western regions of China in terms of land use rationality and intensity, particularly in the wide desert interspersed arid regions. The Ogan-Kucha River Oasis, located in Northwestern China, is an important channel for cultural exchanges between the East and the West on the ancient Silk Road. Low precipitation, high evaporation, low soil fertility and extremely fragile ecosystems are major characteristics of this region. Since the 1950s, after years of construction, the Ogan–Kucha River Oasis has become the main grain and cotton production base in Xinjiang. Particularly in the early 1990s, following the deepening of reform and the birth and establishment of a market economy, the government adjusted industrial structures, enhanced diversification and commodity production, and attached great importance to water conservancy projects. Consequently, the intensity of land resource development continuously increased, and large areas of forest land, shrub land and grassland were cultivated. In addition, increasing prices of agricultural products and a continuous increase in the levels of agricultural mechanization has provided favorable conditions for the expansion of irrigation area in Ogan–Kucha River Oasis over the past two decades (1997–2017); furthermore, the demand for water resources is constantly increasing. The water diversion rates of rivers can reach 60%–80%, which considerably exceeds the threshold of 50% in arid areas. In addition, with the oasis' limited surface water resources, it could never meet the ever-growing demand for water for agricultural and domestic use. Therefore, groundwater has become the second major source of water supply in the oasis. Large amounts of groundwater withdrawals have occurred in different parts of the region. The groundwater exploitation rate has gradually increased, and the accrued groundwater discharge rate has exceeded the recharge rate. In addition, WTD has declined throughout the entire area, with groundwater storage irreversibly lost in some parts of the area, threatening the ecological environment and balance of the oasis [36,37]. WTD fluctuation, which is associated with expansion of area under cultivation, can cause numerous social and ecological problems in oases in arid area regions, including a rapid decline in WTD, thereby increasing pumping costs, reducing basic flow to rivers and wetlands, and increasing groundwater salinity, thus subjecting desert vegetation to salt and water stress. The rising WTD has led to the salinization of soil surfaces, and under strong wind conditions, surface saline alkali sand particles are diffused in the air, which could harm respiratory systems and negatively affect the health of local residents.

This article, which is a case study based on the long-term research in an arid area oasis, overcomes the limitations of the previous research hypothesis that LULC change in the chosen study area has the same impact on groundwater table depth in different spatial locations, while ignoring the spatial heterogeneity of the correlation between the two factors. This study has potential practical applications in revealing the impact of intensive agricultural activities on groundwater resources, accurately determining groundwater variation mechanisms and trends, and identifying past and present spatiotemporal variations, in addition to enabling sustainable development and utilization of groundwater resources in typical fragile arid regions. Therefore, the present research combined land use data derived via remote sensing with field measured WTD data and applied grid cell approaches to investigate the spatiotemporal variations in both WTD and land cover. Subsequently, the local level statistical method GWR was used to reveal the spatiotemporal variation relationships between WTD and cultivated land area changes. The results of this study could increase the knowledge, and understanding of WTD dynamics based on different sources of data and various statistical methods and offer a scientific basis for the development of a more specific and practical plan for the adjustment of agricultural land use patterns with sustainable groundwater exploitation to realize the sustainable management of groundwater resources.

2. Materials and Methods

2.1. Study Area

The Ogan-Kucha River Oasis is located south of the Tianshan Mountains, in the northern margin of the Taklamakan Desert, in Xinjiang Uyghur Autonomous Region, Northwestern China (lat.82°06′–83°37′ E, long.40°55′–41°50′ N) (Figure 1). Northwestern China is an important channel for cultural exchanges between the East and the West on the ancient Silk Road and a major agricultural region and cotton base [38]. The Ogan–Kucha River oasis is a typical mountain-front alluvial plain, surrounded by the Gobi Desert at 980 m above sea level. The project area has a typical extreme continental arid climate with large daily temperature differences according to the climate data provided by the China Meteorological Administration. From 1997 to 2017, the average annual temperature in the oasis was 11.4 °C, and the maximum and minimum temperatures were 41.5 °C and −28.9 °C, respectively. The annual average precipitation was 51.6 mm, and almost 60%–70% of the precipitation was concentrated between May and September, whereas the annual average evaporation was 1192–2863.4 mm [39]. The flat plain contains 23 villages with a total population of approximately 515,000 residents. The total land area is approximately 52,376 km^2, and most of the area is desert. The oasis area is approximately 5609.6 km^2, constituting 10.7% of the total area. Land use types mainly include farmland, forest land, water land, shrub land, and saline alkali soil. Vegetation cover in the study area is relatively low, and the vegetation is dominated by desert species, which are mainly distributed in the oasis–desert ecotone.

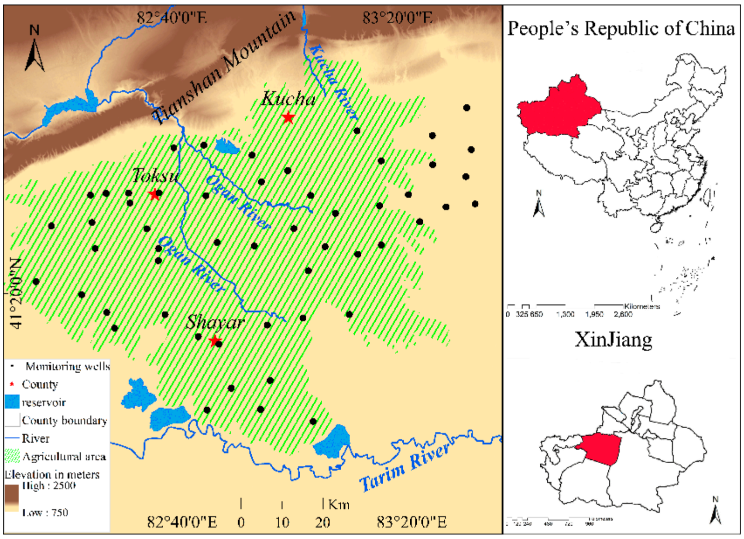

Figure 1. Kucha River Alluvial Delta Oasis.

The total amount of surface water resources in Ogan–Kucha River Oasis is about 30.71 $\times$ 10^8 m^3, and The Ogan River and Kucha River are major surface runoffs entering the oasis, which originate from the northern foot of the Tianshan Mountains. River recharge is mainly provided by snow melts, glacier, and precipitation on the Tianshan Mountain [40]. The Ogan River runs through the central area of the basin. Because the ice and snow-melted water is the main source of river recharge, the runoff is greatly influenced by seasons and is unevenly distributed during the year. Summer accounts for 65% of the annual runoff. In spring, particularly in the sowing period, the runoff is very low, and irrigation water demands are hardly met [41].

2.2. Water Table Depth

WTD in the Ogan–Kucha River Oasis is relatively shallow and is generally <3.5 m. The main sources of groundwater recharge are precipitation, field irrigation, canal system water diversion, and river discharge [42]. In the past 21 years, oasis agricultural land has been expanding under the influence of population growth and water conservation projects. The cultivation center has gradually moved from upstream of the oasis to the downstream, in addition to extending to the oasis-desert ecotone [43]. However, the downstream and oasis peripheral area rivers have dried up. Irrigation is mainly dependent on well irrigation; therefore, groundwater exploitation is gradually increasing.

WTD fluctuations analyzed via observation of well data from 1997 to 2017 and mean annual WTD trends reveal that over the last 21 years, oasis WTD has decreased at a rate of approximately 0.16 m yr^{-1}, ranging from 2.4 m under the soil surface in 1997 to 5.4 m in 2017. The average WTD exhibited an increasing trend, mainly because following the improvement of the drainage system, the main drainage ditches were operated, draining the low-lying area stagnant water. There was an upward trend in the period of 2002–2003, and a rapid decline in the period of 2003–2017. The rise in WTD from 2002 to 2003 was mainly caused by the devastating floods in July 2002 [44]. The seasonal and monthly variations in WTD are closely associated with the irrigation time in areas that are under irrigation and affected by groundwater recharge and discharge [45]. WTD is shallower in the spring and lower in the summer owning to excessive groundwater use for agriculture and withdrawals from the river in summer, leading to reduced groundwater recharge. Monthly variations indicate that WTD is highest in April, followed by May and March, whereas WTD is lowest in October and February. March and April are peak months of spring irrigation every year; thus, WTD begins to rise in these months. Hence, WTD is highest in April and then exhibits a downward trend. Although irrigation occurs from June to September, surface evaporation and crop transpiration increases water consumption, causing fluctuations in WTD. From September to October, winter irrigation occurs, and WTD begins to increase, with another peak in November. Following November, the WTD gradually decreases with phreatic water evaporation and the freezing of soil in winter and reaches the lowest level in the following year from February to March (Figure 2).

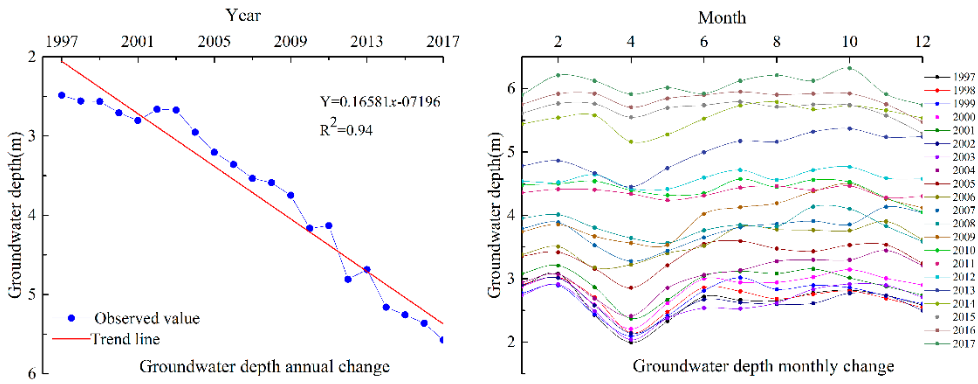

Figure 2. Water table depth (WTD) changes from 1997 to 2017. Source: Water table depth data at 15 day intervals were supplied by the Ogan River Management Office.

2.3. Data Collection

Herein, WTD-measured data and Landsat satellite images were used for analysis. Groundwater observation wells are evenly distributed in the irrigation area and oasis–desert ecotone (Figure 1). WTD data were collected on a monthly basis on the 5th, 15th, and 25th. To avoid the impact of human activities, WTDs in January, February, and December, which are relatively less affected by irrigation, represent the annual WTD. Three Landsat TM/ETM remote sensing images of the years 1997, 2007, and 2017 (30 m spatial resolution) were obtained from the U.S. Geological Survey archives (http://glovis.usgs.gov). All of the images used had been taken in September with high vegetation and minimal cloud cover.

2.4. Methods

2.4.1. Geostatistical Analysis

Groundwater is considered as a regionalized variable with its randomness and structural characteristics. Geostatistical methods have the capacity to describe spatial variability characteristics of variables with both stochastic and structural properties [46]. Kinging interpolation is the most commonly used geostatistical analysis method and is the optimal linear unbiased method for estimating the value of regionalized variables at an unsampled locations based on the available data of regionalized variables and structural features of a variorum. Kinging interpolation methods can be divided into simple kinging (SK), ordinary kinging (OK), and universal kinging (UK) [47]. Based on previous studies, among the different kinging interpolation methods, OK has been demonstrated to be applicable and reliable in the revelation of spatial and temporal variations in WTD in arid regions [48,49]. OK estimates the spatial variation of variables according to the distribution of sampling points and variogram models when calculating unknown points [50,51]. The kinging estimate of variable Z at point x, z(x), is a linear weighted sum of n observations surrounding the estimate (Equation (1)):

$$z(x) = \sum_{i=1}^{n} \lambda_i^1 z(x_i), \tag{1}$$

where n is the number of observation points, λ_i are the weights and z(x_i) is the known value of variable Z at sampling site x_i [52]. The interpolation variance σ_{ok} in each point is calculated based on the following equation:

$$\sigma_{ok}^2 = \sum_{i=1}^{n} \lambda_i \gamma_{0i} + \mu - \gamma_{00}, \tag{2}$$

where γ_{0i} and γ_{00} are the average variogram corresponding to h situated at equal distances to the i to observation point and point of interest and at a distance equal to zero, respectively, and μ is the Lagrange multiplier [53].

2.4.2. Mapping Land Cover and Land Use

In the present study, decision tree (DT) classification was performed to map the following six LULC categories: cultivated land, shrub covered area, water body, built-up area, salinized area and bare land [54]. The basic idea of DT classification is to use one or more independent variables to predict the most similar type for each sample. DT has the capacity to handle data measured on different scales, and the flexibility to handle nonlinear relationships between features and classes. In contrast to various classification methods, DT can be trained relatively rapidly and rapidly executed; it can also realize higher levels of classification accuracy for multispectral data [55]. We applied spectral math to the acquired normalized difference vegetation index, modified normalized difference water index, normalized difference build-up index, salt index, digital elevation model, and band ratio data. The indices were applied as input variables in the DT classifier. Subsequently, based on the optimal thresholds of each index, we established a DT model for land use classification in the study area. The classification results obtained from the DT classification were overlapped with the original data, and a visual interpretation test was conducted. The results were largely consistent with the actual situation. To verify the accuracy of the classification, we randomly collected 800–1000 training samples per land cover class respectively and calculated the confusion matrix. The training samples were interpreted based on Landsat and Google Earth Images and verified using field investigations and our expert knowledge of the research area. Accuracy assessment using the confusion matrix revealed overall accuracies ranging between 83.2% and 91.4% for the classified land cover types. In particular, the accuracy for the cultivated land class was higher than 86.5%.

2.4.3. Grid Cell Method

To discuss the spatiotemporal agricultural land area change and WTD variation, we applied a grid cell approach. We built vector polygon grid cells at the boundary of the study area, and each cell was assigned unique and appropriate identification (ID) numbers, which facilitated the linking of the agricultural land and WTD data [56]. Subsequently, we converted each raster agricultural land and WTD map to vector grids, and intersected the grid with empty grid cells using the spatial join function in ArcGIS to calculate the percentage area of agricultural land data and WTD in each grid cell. When calculating the percentage of agricultural land area within a cell, we divided the sum of the agricultural land area within each grid cell by the cell area. The WTD within one grid cell was the average value for each piece. Considering the research objectives, study area coverage, and computational efficiency, based on repeated experiments, the size of each vector grid cell was determined to be 1 × 1 km, obtaining a total of 13,132 grid cells.

2.4.4. Geographically Weighted Regression (GWR) Analysis

We applied GWR analysis to explore the local spatial relationship between agricultural land and WTD change. GWR is a non-parametric local spatial regression analysis method for modeling the relationship between dependent and independent variables in different spatial subdomains with spatial variations [54,55]. The regression coefficients of independent variables in this method vary with spatial locations. Therefore, it has great local analysis capacity for spatial data [57].

3. Results

3.1. Water Table Depth Variations

To quantitatively describe the variation characteristics of WTD, a Gaussian function fitted semivariogram was used to model the WTD for the years 1997, 2007, and 2017 (Table 1). The results show that the nugget and sill values considerably increased from 1997 to 2017, indicating that as the spatial heterogeneity caused by stochastic (artificial) factors of WTD are gradually reinforced and as the degree of spatial heterogeneity increases, the difference in WTD between oasis and desert areas increases. The nugget and sill value ratio (GD) increased from 0.18 in 1997 to 0.31 in 2017, indicating an increase in the correlation of WTD between different locations. From 1997 to 2007, a strong spatial correlation was observed, i.e., change in WTD in a certain area would considerably influence WTD in an adjacent area. Similarly, from 1997 to 2017, the GD effect gradually increased, indicating that the influence of WTD structural factors decreased on a yearly basis, whereas the influence of stochastic factors increased. The range was 19.27 km in 1997 and 22.88 km in 2017, indicating that the influence of human activities on WTD had increased, in addition to the range of autocorrelation.

Table 1. Theoretical model of the semivariogram function of WTD and its relevant parameters.

Year	Model	Nugget	Sill	GD	Range/m	R^2
1997	Gaussian	0.42	2.228	0.18	19278	0.78
2007	Gaussian	1.48	5.969	0.25	25392	0.66
2017	Gaussian	3.22	10.449	0.31	22881	0.52

In conclusion, the randomness of WTD in the Ogan-Kucha river oasis has been gradually increasing. The effects of natural spatial structure factors, such as topography, landscape, climate and soil types are weakening, whereas the effects of human driven stochastic factors, such as urban construction, farming, planting systems, irrigation, and drainage intensity effects are gradually being reinforce. Human activities are the main factors influencing the changes in WTD.

Spatial distribution of WTD at different periods is presented in Figure 3. The data conforming to normal distribution is the basic condition for applying OK interpolation, and the test results found that the data did conform to normal distribution. Based on the semi-variance function model and the observation data, spatial interpolation was performed for the uninvestigated sites. According to the map, the study area WTD spatial distribution characteristics at different periods were essentially similar from north to south. However from the alluvial fan upper parts to the lower parts and from the interior of the oasis to the oasis–desert ecotone, WTD gradually become shallower. Along the main diversion canals of the Kucha, Shayar, Toksu counties, WTD was shallow and gradually deepened as one moved away from the main canal. In addition, surface soil salinization was relatively severe in the northeast section of the study area, and WTD was shallowest in the area compared to the other regions. The difference in WTD between the interior region of the oasis and the oasis–desert ecotone was relatively obvious, particularly in the northeastern part, and the difference ranged from approximately 2 to 4 m. At different time periods, the spatial distribution of WTD in a few areas was not obvious and remained relatively stable in 1997. However, the spatial difference gradually increased, and considerable fluctuation occurred.

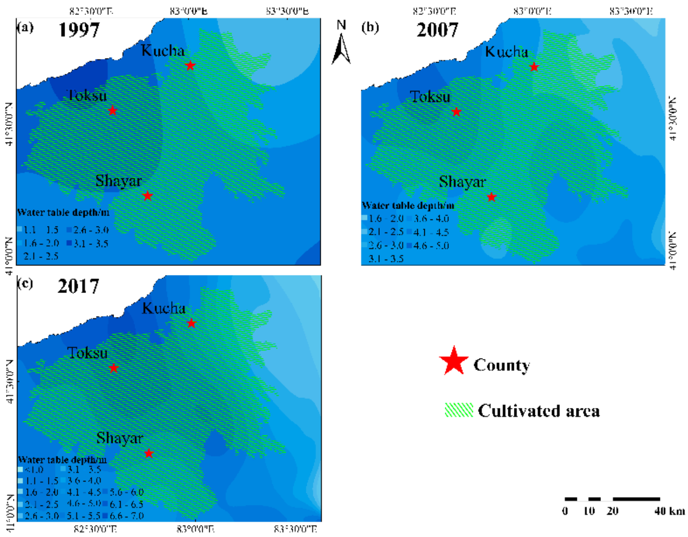

Figure 3. The distribution of WTD.

The grid-cell based spatial variation in WTD from 1997 to 2017 is illustrated in Figure 4. The Ogan–Kucha River Oasis WTD inter-annual variation trends in different parts of the alluvial fan were essentially similar, and all trends exhibited fluctuation and general increments. However, considerable differences existed between the amplitudes of different regions. The declines in WTD in area under the irrigation area were much greater than those in the oasis–desert ecotone. In addition, WTD changes displayed spatial variation with altitude. The change rule was more rapid in the upper and middle parts of the alluvial fan, with decreasing amplitude between 1.8m and 3.4m, belong to a significant decline. In the lower and western parts of the alluvial fan, WTD decreased by 0.76–1.5 m. The change was relatively slow, and belonged to the stable descending type. In the eastern oasis–desert ecotone, WTD marginally decreased and some areas exhibited increments in WTD. Therefore, the section belonged to a steadily declining–locally rising mixed type. From 1997 to 2007, the area with a WTD decline lower than 1 m constituted 58.8% of the total area, a decline between 1–1.5 m constituted 29.8%, and areas with declines greater than 1.5 m constituting only 11.7% of the total area. The results indicate that there was no obvious WTD fluctuation in the entire area in the period between 1997 and 2007. During the decade of 2007–2017, both increments and decrements were observed in WTD. However, most of the regions generally had sharp declines, and only the eastern part of the alluvial fan had small areas with marginal increments. Areas with 1.5–2 m and 2–2.5 m declines constituted 33.6% and 15.5% of the total area, respectively. Areas with <1 m decrements constituted 28.9% of the total area, whereas areas with >2.5 m declines constituted 3.8% of the total area.

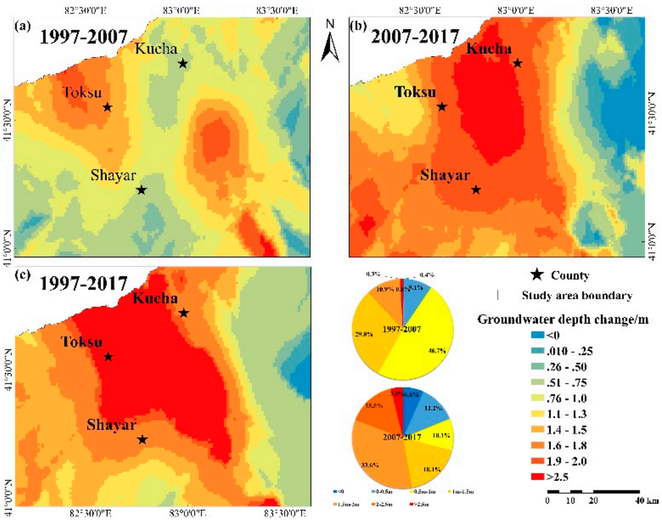

Figure 4. WTD changes from 1997 to 2017.

3.2. Land Cover Change Patterns

Study area LULC classification maps for the two decades and their total areas from 1997 to 2017 are shown in Figure 5. Several key trends are observed in land-cover changes over the study period. The area under cultivation increased markedly, and decreases in shrub-covered and salinized areas were observed. The cultivated area nearly tripled across the two decades, increasing from 16.8% in 1997 to 46.1% in 2017, whereas the shrub land reduced to accommodate the expansion of land under cultivation, decreasing from 31.1% in 1997 to 12.6% in 2017. Salinized areas exhibited a consistent decreasing trend, decreasing from 18.02% in 1997 to 6.15% in 2017. In addition, the trend was most apparent in irrigated districts. The reason for the trend in the salinized area is that in the late 1990s, agricultural irrigation and the construction of supporting drainage infrastructure was performed in the Ogan-Kucha River Oasis. Therefore, drainage conditions were significantly improved, and the uncontrolled rise in WTD was controlled, in turn preventing surface soil salinization. Land cover under water bodies also decreased from 1.5% in 1997 to 0.66% in 2007; however, it increased to 3.1% in 2017, which could be related to irrigation. Drainage systems have generally improved, and the utilization efficiency of the canal system has been increased. There was a slight increase in the built up area across the two decades, from 0.1% in 1997 to 0.6% in 2017.

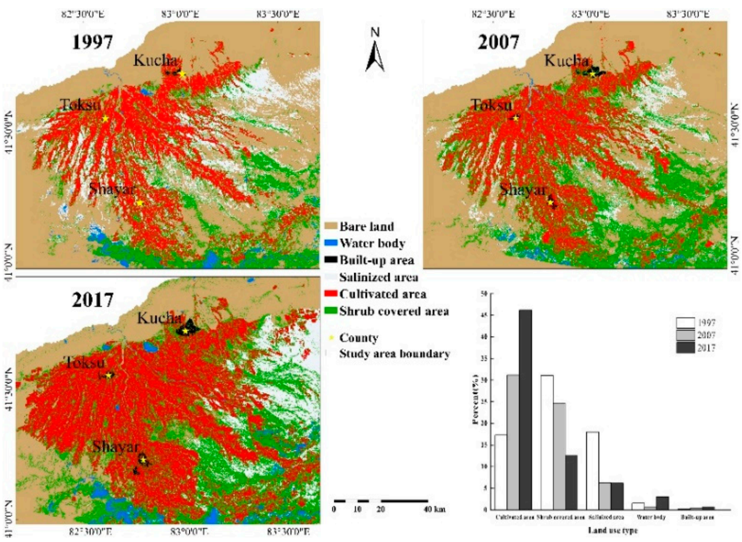

Figure 5. Land use and land cover (LULC) maps of Ogan–Kucha River Oasis from 1997 to 2017.

In most previous studies, spatial variations in land cover classes was revealed using landscape metrics. However, such an approach cannot specifically describe the spatial dynamics and distribution of LULC. T overcome this limitation, we applied a grid cell approach on overlapping land cover maps on the empty grid cells and calculated the percentages of the land cover types within each cell. The attributed values of each grid cell represent the percentage change in land-cover categories during the study period at a scale of 1 km^2.

Figure 6 presents the grid-cell based spatial variations for cultivated land from 1997 to 2017. Over the two decades, cultivated land continuously expanded throughout the research area at different rates. Compared with the cultivated land in the interior of the oasis, the growth rate was more rapid and significant in the periphery of the oasis (Figure 6c). Considering the administrative areas, among the different counties, the area under cultivation increased most substantially in Kucha County. We also examined the spatial distribution of cultivated land at different time intervals. As shown in Figure 6a, from 1997 to 2007, in addition to the individual areas, no considerable large-scale growth trends were observed in the study area for the area under cultivation. There was relatively slow steady growth accompanied by slight reductions in some areas. Decrements were largely observed in the urban core where the build-up area had increased and in the periphery of the oasis, which was not reached by the river. The cultivated land increased markedly from 2007 to 2017, with the largest increases observed at the periphery of the oasis.

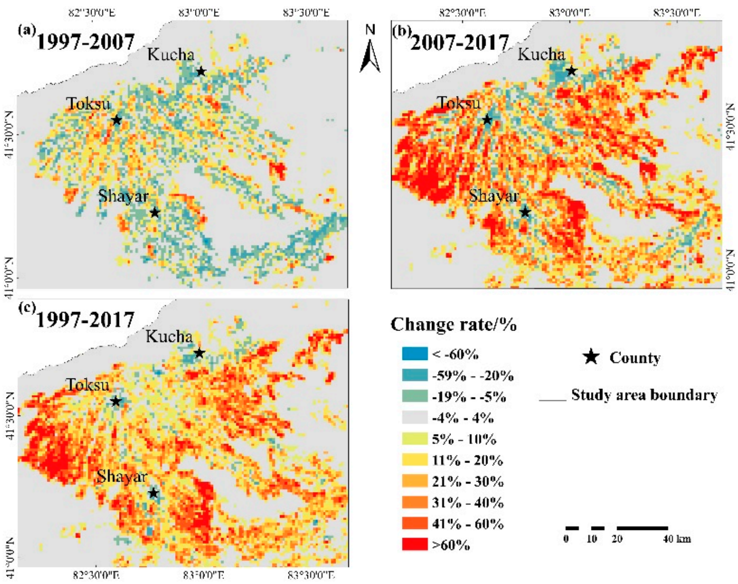

Figure 6. Percentage change of cultivated area in 1 km^2 grid cells from 1997 to 2017.

3.3. Relationship between WTD Change and Land Cover Classes

In the present study, we employed different statistical methods to examine the relationship between the WTD change and area percentage area of the different land-cover categories at different time intervals based on 13,132 grid cells.

Table 2 presents the results of the correlation analysis for the different time intervals. Multiple significant relationships existed between different land cover categories and WTD. The highest relationship was between WTD and the changes in cultivated land area. The correlation coefficients were 0.31, 0.51, and 0.59 for the 1997–2007, 2007–2017, and 1997–2017 decades, respectively. The correlation increased with the expansion of cultivated land, suggesting that the continuous expansion of agricultural land was the major driving factor causing WTD changes in the arid areas that are highly dependent on groundwater resources. A second significant relationship was observed between WTD and salinized land. In contrast to cultivated land, salinized land was negatively affected by WTD fluctuations. As severe surface soil salinization is caused by higher WTD, reduction in WTD gradually reduced salt accumulation on the surface. In addition, a relationship existed between WTD changes and shrub cover. WTD changes influenced the growth of shrubs. More shrub species that grew and thrived in areas with high WTD were observed. However, shrubs were sparse in areas with low WTD. No close relationships were observed between WTD and other LULC types.

Table 2. Pearson's correlation coefficient (r) between the land cover and WTD change.

Period	Land Use Type	OLS	R^2	Pearson Coefficient
1997–2007	Bare land	y =0.00001845x + 0.962	0.06	0.11**
	Water body	y = −0.000000246x + 0.969	0.23	−0.04
	Built-up area	y = 0.00001954x + 0.968	0.01	0.06*
	Salinized area	y = −0.00001558x + 0.961	0.28	−0.16**
	Cultivated area	y = 0.00003652x + 0.965	0.3	0.31**
	Shrub covered area	y = −0.00002525x + 0.949	0.15	−0.15**
2007–2017	Bare land	y = 0.00009034x + 1.539	0.11	0.17**
	Water body	y = −0.00000592x + 1.346	0.13	−0.01
	Built-up area	y = 0.00001103x + 1.344	0.08	0.05**
	Salinized area	y = −0.0000121x + 1.373	0.38	−0.39**
	Cultivated area	y = 0.0000691x + 1.344	0.58	0.51**
	Shrub covered area	y = −0.00004784x + 1.364	0.34	−0.25**
1997–2017	Bare land	y = 0.0008145x + 2.515	0.12	0.18**
	Water body	y = −0.0000072x + 2.320	0.12	−0.05**
	Built-up area	y = 0.00009367x + 2.310	0.05	0.05**
	Salinized area	y = −0.00001412x + 2.285	0.36	−0.39**
	Cultivated area	y = 0.00003355x + 2.266	0.48	0.59**
	Shrub covered area	y = −0.00003317x + 2.351	0.37	−0.29**

** Correlation is significant at the 0.01 level (two-tailed).

To further investigate the correlation between WTD and land-cover categories, we applied GWR analysis. We largely explored the nature of the spatial relationship between the WTD and cultivated land change, which was considered the major explanatory variable that could cause WTD fluctuation. GWR models produce a set of local parameter estimates, and local R square values. Based on the maps of the local regression results of the GWR model, we can visualize the spatially varying relationships between WTD and LULC change.

The local slope parameters and local R squares from the GWR model for cultivated land and WTD changes are shown in Figure 7. The GWR model analysis results indicated that in contrast to the ordinary linear regression model, the influence of cultivated land area change on WTD was spatially non-stationary. Both significant positive and negative relationships existed and the intensity of effects was spatially differentiated. Based on a temporal perspective, regression coefficient value ranges were −0.0015−0.002 between 1997 and 2007 year, −0.0091−0.00187 in between 2007 and 2017, and −0.0527–0.003 between 1997 and 2017. From 1997 to 2017, the range of regression coefficient increased, i.e., the influence of cultivated land on WTD was enhanced. Considering the positive and negative coefficient values, most areas in the study area were largely positively correlated. From a spatial distribution perspective, high positive relationships and higher R squares between cultivated land and WTD changes were observed in the oasis–desert ecotone, whereas relatively lower correlations and R square values were associated with the oasis interior. The results are associated with reductions in WTD and increases in groundwater withdrawals were associated with the significant expansion of the area under cultivation. Notably, the amount of groundwater exploitation has been increasing in the oasis–desert ecotone from 1997 to 2017. We also explored the spatial patterns of relationships between cultivated land and WTD change at different time intervals. From 1997 to 2007, the effects of cultivation on WTD were mainly concentrated within the oasis interior, and correlation between the change in cultivated land change and WTD was largely similar in the entire area. However, the correlation coefficient was not very high. Considering the land under cultivation, surface water can essentially meet the irrigation water demands. Therefore, groundwater exploitation is relatively low and there is generally low dependence on groundwater. Both positive and negative correlations exist between the change in cultivated land and WTD in the peripheral oasis–desert ecotone of the oasis; this is mainly because the oasis–desert ecotone has not yet been reclaimed on a large scale. Therefore, no WTD fluctuation occurs over a large area owing to the expansion of cultivated land in the oasis–desert ecotone area. From 2007 to 2017, with the continuous expansion of cultivated land in the oasis–desert ecotone, relatively strong positive relationships and higher R squares were observed in the area, particularly in the eastern part of the study area.

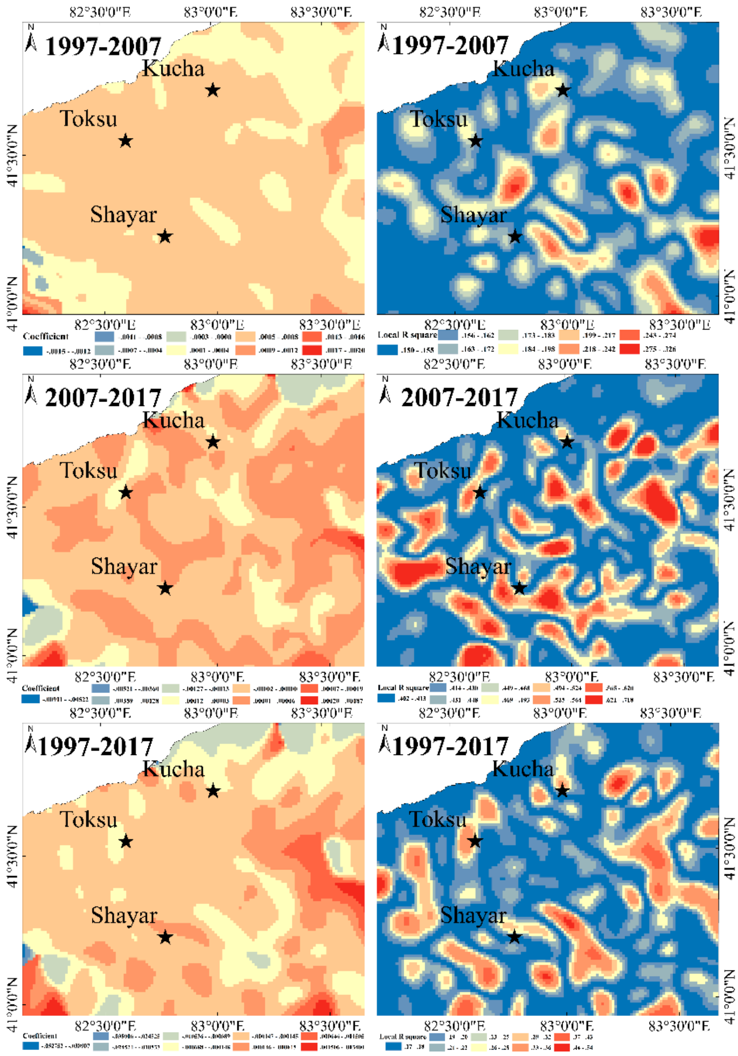

Figure 7. Spatial variation of regression outputs from the GWR model for agricultural land and WTD change from 1997 to 2017.

4. Discussion

The Ogan–Kucha River Oasis is located in an arid region. It has unique landscape characteristics and a fragile ecological environment. Over the past two decades, the oasis has experienced rapid economic growth and has conducted considerable farmland reclamation activities. Consequently, groundwater exploitation has been intensified, with serious implications for WTD [58]. Oasis typically experience high rates of soil salinization. If the evaporation rate and WTD are too high, surface soil salinization occurs, and the natural vegetation is subjected to salt stress. In addition, groundwater is a major water source for maintaining the oasis' natural vegetation growth. If WTD is too low, vegetation is affected by water stress, resulting in vegetation degradation or death and even desertification. Therefore, understanding changes in WTD due to human activities and determining the WTD threshold is key in controlling soil salinization and maintaining natural vegetation in oasis–desert ecotone. Various studies have explored the relationship between LULC and WTD change. However, most studies have employed global level statistics to discuss spatiotemporal changes in WTD [59–62]. Herein, we combined both satellite and ground measured data in grid cells and applied local level GWR statistical methods to understand spatiotemporal characteristics, trends, and the correlation between LULC and WTD change in detail.

Objective area WTD distributions reveal significant spatiotemporal differences in the entire region (Figure 3). From the spatial distribution, the groundwater in the oasis-desert ecoton is shallower than in irrigation areas. Generally, Oasis–desert ecotone groundwater recharge mainly relies on precipitation infiltration, and with the extremely high evaporation rates, precipitation does not contribute to the WTD rise, and hence, the WTD is relatively low. However, the oasis–desert ecotone is located at the edge of the irrigation area, while the Ogan–Kucha River Oasis is characterized by high altitudes in the north and low altitudes in the south [63]. Such topographic features cause the alkaline water to be discharged by the irrigation district and groundwater to flow from north to south, which eventually gathers downstream and at the edge of the oasis, increasing the WTD. In addition, such areas have less human disturbance and relatively low levels of groundwater exploitation compared with the interior of the oasis, resulting in shallower WTD. Based on the WTD variations obtained from the grid-cell (Figure 4), WTD in the alluvial fan increased over the past two decades, and the WTD drops in the irrigation district were potentially due to the agricultural development. Compared with the 2007–2017 decade, WTD was higher in the first decade (1997–2007), and the declining trend was not obvious, mainly because in the beginning of 1997, the newly-reclaimed farmland was mostly low yielding, and flooding irrigation was the only way of minimizing salinization and increasing productivity [64]. Therefore, high amounts of irrigation water gradually increased WTD. After 2007, with the acquisition of improved drainage equipment and improvement of drainage conditions, the increase in WTD was effectively controlled.

The spatial distribution patterns of LULC change in the Ogan–Kucha River Oasis indicated rapid increase in cultivated land and severe degradation of shrub land from1997 to 2017 (Figure 5). Together with the expansion in agricultural area, shrub land, salinized land, and bare land has been converted to cultivated area. The cultivated area exhibited high rates of expansion at different rates of change, spreading to the periphery of the oasis (Figure 6). The spread was likely due to the continuous population growth, gradual increase in demand for food production coupled with rising cotton prices, and enhanced farmer enthusiasm for production, with more arable land required to meet the ever-growing demands [65–67]. In addition, with the continuous development of the social economy, extensive water conservation infrastructure has been constructed in the entire area, facilitating large-scale reclamation of wasteland. In addition, the availability of water conservation infrastructure has changed the original expansion model of oasis cultivated land. The newly reclaimed cultivated land is gradually transferred to the periphery of the oasis from the inner rivers of the oasis and the areas surrounding irrigation wells.

Compared with the linear regression, the GWR model can describe the spatiotemporal relationship between cultivated land and WTD in greater detail from a spatial heterogeneity perspective. GWR results showed that the effects of cultivated area change on the WTD were considerably variable in space. The relationship between WTD and change in cultivated land area over the three time intervals revealed that both the irrigation area and oasis–desert ecotone WTD were positively correlated with cultivated land area variations, and the correlations significantly increased with extensive expansion of the area under cultivation (Table 2; Figure 7). The relationship between cultivated land area and WTD in the oasis–desert ecotone was more prominent than that in the oasis interiors. This observation implies that the center of the cultivated land expansion gradually moved from upstream of the alluvial fan to downstream of the alluvial fan and extended to the periphery of the Oasis.

Based on the results of the present study, there are different interactions between WTD and cultivated land area change in different parts of the study area. Furthermore, the degree of correlation is also different. Therefore, blindly reclaiming cultivated land and overexploiting groundwater resources would pose risks for the local ecological environment. Our research provides some insights on the WTD variation and LULC change and the spatiotemporally varied relationships between the two factors. These insights could facilitate changes to the current unsustainable agricultural production models and land and water resource utilization models together with improving the efficiency of land and water resource development and utilization, while providing local governments with decision-making tools. However, this study has certain limitations: first, only a single factor (cultivated land change) was considered herein for the regression analysis. Typically, changes in WTD and its spatial heterogeneity are also influenced by topography, elevation, microclimate differences, and human activities. Second, water table observation wells are mainly distributed in the irrigation area and are less or unevenly spread in the oasis–desert ecotone, which could negatively affect the reliability of the results. Owing to these limitations, considering multiple driving factors with sufficient data is necessary in future studies.

5. Conclusions

Based on the land use changes observed remote-sensing and geostatistical methods, the present study analyzed the spatiotemporal variation of WTD and LULC together with the local correlation relationships between WTD and cultivated land area change and explained the spatial non-stationary characteristics of these relationships. In the last 21 years, the effects of human activities on the groundwater in the Ogan–Kucha River Oasis have been increasing, and human activities have become the major factor influencing the change in WTD. Significant increases in groundwater exploitation between 1997 and 2017 have increased WTD coupled with population growth and farmland expansion. In terms of spatial distribution changes, WTD has gradually deepened in the oasis irrigation district and gradually become shallower in the oasis fringe oasis–desert ecotone. Large-scale changes in LULC have occurred together with a rapid increase in economic and human demands from 1997 to 2017. In addition, cultivated land rapidly increased while shrub land area significantly decreased, and fragmented landscape was gradually turned into farmland. The cultivated land expansion mainly occurred at the alluvial fan edge and in the oasis–desert ecotone, thereby considerably and rapidly degrading shrub land.

Spatiotemporal correlation analysis using OLS and GWR models revealed that WTD was positively correlated with cultivated land change during 1997–2017. However, the intensity of the spatiotemporally varying relationships based on land use types in relation to WTD changes is not constant over time and space; it varies over space owing to spatial heterogeneity, according to the grid cell analysis based on the local level regression analysis. With increasing cultivated land area, the relationship between WTD and cultivated land change has become more significant, as the cultivated land has gradually extended from the central regions of the oasis to the edge and oasis–desert ecotone. The correlation between WTD and cultivated land change is also more prominent in the oasis–desert ecotone than that in the oasis interior. The results of the present study are crucial for both efficient groundwater management and land use research, and these results could facilitate policy makers' land use planning activities with regard to groundwater, based on the observed effects of activities over the past two decades. The spatiotemporal correlation analysis using local statistics methods facilitated the demonstration of the process of WTD change and its close relation with human agricultural activities, in addition to the response in terms of spatiotemporal fluctuation in WTD, which is caused by the continuous expansion of irrigation area in the oasis. Furthermore, a spatial difference was observed in the relationship. Therefore, land use and water resource management decisions should be modified in different parts of the study area based on the spatial heterogeneity.

Author Contributions: J.D. and M.A. designed the project; M.A. and J.W. did the field work and collected, analyzed the data; M.A. and J.D. wrote and edited the paper; J.W. and N.N. reviewed the manuscript. All authors read and approved the final manuscript.

Acknowledgments: This research was supported by grants from the National Natural Science Foundation of China [NO.41771470 and NO.U1603241]. The authors express gratitude to the anonymous reviewers and the editors for their valuable comments and editorial suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Singh, G. Effect of Polluted Surface Water on Groundwater: A Case Study of Budha Nullah. *Science* **2013**. [CrossRef]
2. Musaoglu, N.; Tanik, A.; Gumusay, M.U.; Dervisoglu, A.; Bilgilioglu, B.B.; Yagmur, N.; Bakirman, T.; Baran, D.; Gokdag, M.F. Long-term Monitoring of Wetlands via Remote Sensing and GIS: A case study from Turkey. In Proceedings of the 2nd International Conference on Climate Change, Colombo, Sri Lanka, 15–16 February 2018.
3. LaMoreaux, J.W. Thematic issue: Groundwater resources management. *Environ. Earth Sci.* **2013**, *70*, 1943. [CrossRef]
4. Taylor, R.G.; Scanlon, B.; Döll, P.; Rodell, M.; Beek, R.V.; Wada, Y.; Longuevergne, L.; Leblanc, M.; Famiglietti, J.S.; Edmunds, M. Ground water and climate change. *Nat. Clim. Chang.* **2013**, *3*, 322–329. [CrossRef]
5. Gao, X.; Huo, Z.; Xu, X.; Qu, Z.; Huang, G.; Tang, P.; Bai, Y. Shallow groundwater plays an important role in enhancing irrigation water productivity in an arid area: The perspective from a regional agricultural hydrology simulation. *Agric. Water Manag.* **2018**, *208*, 43–58. [CrossRef]
6. Guo, H.; Ling, H.; Xu, H.; Guo, B. Study of suitable oasis scales based on water resource availability in an arid region of China: A case study of Hotan River Basin. *Environ. Earth Sci.* **2016**, *75*, 984. [CrossRef]
7. Yang, Z.; Zhou, Y.; Wenninger, J.; Uhlenbrook, S. A multi-method approach to quantify groundwater/surface water-interactions in the semi-arid Hailiutu River basin, northwest China. *Hydrogeol. J.* **2014**, *22*, 527–541. [CrossRef]
8. Aeschbachhertig, W.; Gleeson, T. Regional strategies for the accelerating global problem of groundwater depletion. *Nat. Geosci.* **2012**, *5*, 853–861. [CrossRef]
9. Cotterman, K.A.; Kendall, A.D.; Basso, B.; Hyndman, D.W. Groundwater depletion and climate change: Future prospects of crop production in the Central High Plains Aquifer. *Clim. Chang.* **2018**, *146*, 187–200. [CrossRef]
10. Zheng, X.; Zhu, J.J.; Yan, Q.L.; Song, L.N. Effects of land use changes on the groundwater table and the decline of Pinus sylvestris var. mongolica plantations in southern Horqin Sandy Land, Northeast China. *Agric. Water Manag.* **2012**, *109*, 94–106. [CrossRef]
11. Liu, Y.; Jiang, X.; Zhang, G.; Xu, Y.J.; Wang, X.; Qi, P. Assessment of Shallow Groundwater Recharge from Extreme Rainfalls in the Sanjiang Plain, Northeast China. *Water* **2016**, *8*, 440. [CrossRef]
12. Singh, C.K.; Mukherjee, S.; Shashtri, S. Modeling impacts of change in Landuse/Landcover on groundwater system in Shiwaliks of Punjab using Remote Sensing and GIS. *J. Mammal.* **2009**, *88*, 1098–1111.
13. Sun, Z.; Opp, C.; Hennig, T.; Marold, U. Impacts and Implications of Major Changes Caused by the Three Gorges Dam in the Middle Reaches of the Yangtze River, China. *Water Resour. Manag.* **2012**, *26*, 3367–3378. [CrossRef]
14. Ghazavi, R. Impacts of land-use change on groundwater resources using remote sensing and numerical modeling. *J. Biodivers. Environ. Sci.* **2016**, *9*, 149–157.
15. Scanlon, B.R.; Reedy, R.C.; Stonestrom, D.A.; Prudic, D.E.; Dennehy, K.F. Impact of land use and land cover change on groundwater recharge and quality in the southwestern US. *Glob. Chang. Biol.* **2010**, *11*, 1577–1593. [CrossRef]
16. Dahlhaus, P.G.; Evans, T.J.; Nathan, E.L.; Cox, J.W.; Simmons, C.T. Groundwater-level response to land-use change and the implications for salinity management in the West Moorabool River catchment, Victoria, Australia. *Hydrogeol. J.* **2010**, *18*, 1611–1623. [CrossRef]
17. Sun, D.; Zhao, C.; Wei, H.; Peng, D. Simulation of the relationship between land use and groundwater level in Tailan River basin, Xinjiang, China. *Quat. Int.* **2011**, *244*, 254–263. [CrossRef]
18. Bhat, V.; Prajwal, M.; Shetty, A.; Srivastava, A.; Bhosale, R. Spatiotemporal Relationship Linking Land Use/Land Cover with Groundwater Level. In *Groundwater*; Springer: Berlin, Germany, 2018.

19. Wang, J.; Gao, Y.; Wang, S. Land Use/Cover Change Impacts on Water Table Change over 25 Years in a Desert-Oasis Transition Zone of the Heihe River Basin, China. *Water* **2016**, *8*, 11. [CrossRef]
20. Elmahdy, S.I.; Mohamed, M.M. Land use/land cover change impact on groundwater quantity and quality: A case study of Ajman Emirate, the United Arab Emirates, using remote sensing and GIS. *Arabian J. Geosci.* **2016**, *19*, 722. [CrossRef]
21. Mcmillen, D.P. Geographically Weighted Regression: The Analysis of Spatially Varying Relationships. *Am. J. Agric. Econ.* **2002**, *86*, 554–556. [CrossRef]
22. Bellehumeur, C.; Legendre, P. Multiscale sources of variation in ecological variables: Modeling spatial dispersion, elaborating sampling designs. *Landsc. Ecol.* **1998**, *13*, 15–25. [CrossRef]
23. Tu, J.; Xia, Z.G. Examining spatially varying relationships between land use and water quality using geographically weighted regression I: Model design and evaluation. *Sci. Total Environ.* **2008**, *407*, 358–378. [CrossRef]
24. Yan, J.F.; Chen, X.; Luo, G.P.; Guo, Q.J. Temporal and spatial variability response of groundwater level to land use/land cover change in oases of and areas. *Chin. Sci. Bull.* **2006**, *51*, 51–59. [CrossRef]
25. Langroodi, S.H.M.; Masoum, M.G.; Nasiri, H.; Javi, S.T. Spatial and temporal variability analysis of groundwater quantity to land-use/land-cover change in the Khanmirza agricultural plain in Iran. *Arab. J. Geosci.* **2015**, *8*, 8385–8397. [CrossRef]
26. Moukana, J.A.; Asaue, H.; Koike, K. Co-kriging for modeling shallow groundwater level changes in consideration of land use/land cover pattern. *Environ. Earth Sci.* **2013**, *70*, 1495–1506. [CrossRef]
27. Javi, S.T.; Malekmohammadi, B.; Mokhtari, H. Application of geographically weighted regression model to analysis of spatiotemporal varying relationships between groundwater quantity and land use changes (case study: Khanmirza Plain, Iran). *Environ. Monit. Assess.* **2014**, *186*, 3123–3138. [CrossRef]
28. Brunsdon, C.; Fotheringham, A.S.; Charlton, M.E. Geographically Weighted Regression: A Method for Exploring Spatial Nonstationarity. *Geogr. Anal.* **2010**, *28*, 281–298. [CrossRef]
29. Brown, S.; Versace, V.L.; Laurenson, L.; Ierodiaconou, D.; Fawcett, J.; Salzman, S. Assessment of Spatiotemporal Varying Relationships Between Rainfall, Land Cover and Surface Water Area Using Geographically Weighted Regression. *Environ. Model. Assess.* **2012**, *17*, 241–254. [CrossRef]
30. Clement, F.; Orange, D.; Williams, M.; Mulley, C.; Epprecht, M. Drivers of afforestation in Northern Vietnam: Assessing local variations using geographically weighted regression. *Appl. Geogr.* **2009**, *29*, 561–576. [CrossRef]
31. Luo, J.Q.; Du, P.J.; Samat, A.; Xia, J.S.; Che, M.Q.; Xue, Z.H. Spatiotemporal Pattern of PM2.5 Concentrations in Mainland China and Analysis of Its Influencing Factors using Geographically Weighted Regression. *Sci. Rep.* **2017**, *12*. [CrossRef]
32. Parmentier, B.; McGill, B.J.; Wilson, A.M.; Regetz, J.; Jetz, W.; Guralnick, R.; Tuanmu, M.N.; Schildhauer, M. Using multi-timescale methods and satellite-derived land surface temperature for the interpolation of daily maximum air temperature in Oregon. *Int. J. Climatol.* **2015**, *35*, 3862–3878. [CrossRef]
33. Lu, B.B.; Charlton, M.; Harris, P.; Fotheringham, A.S. Geographically weighted regression with a non-Euclidean distance metric: A case study using hedonic house price data. *Int. J. Geogr. Inf. Sci.* **2014**, *28*, 660–681. [CrossRef]
34. Jaimes, N.B.P.; Sendra, J.B.; Delgado, M.G.; Plata, R.F. Exploring the driving forces behind deforestation in the state of Mexico (Mexico) using geographically weighted regression. *Appl. Geogr.* **2010**, *30*, 576–591. [CrossRef]
35. Nazeer, M.; Bilal, M. Evaluation of Ordinary Least Square (OLS) and Geographically Weighted Regression (GWR) for Water Quality Monitoring: A Case Study for the Estimation of Salinity. *J. Ocean Univ. China* **2018**, *17*, 305–310. [CrossRef]
36. Shabiti, M.; Yan-Hong, L.I. Analysis on Water-saving Potentiality and the Issue of Water Resources in the WeiGan-KuChe River Delta Oasis. *J. Arid Land Resour. Environ.* **2007**, *21*, 23–28.
37. Wang, J.; Zhang, F.; Haiyang, Y.U.; Ren, Y.; Zhang, Y. Analysis on the Hydrological and Ecological Characteristics Based on the LUCC in Weigan and Kuqa River. *Res. Soil Water Conserv.* **2016**, *23*, 236–242.
38. Fei, W.; Ding, J.; Yang, W.; Zhou, Q.; Yang, X.; Wang, Q. Sensitivity analysis of soil salinity and vegetation indices to detect soil salinity variation by using Landsat series images: Applications in different oases in Xinjiang, China. *Acta Ecol. Sinica.* **2017**. [CrossRef]

39. Ding, J.; Juan, Q.U.; Sun, Y.; Zhang, Y. The retrieval model of soil salinization information in arid region based on MSAVI-WI feature space: A case study of the delta oasis in Weigan-Kuqa watershed. *Geogr. Res.* **2013**, *32*, 223–232.
40. Ding, J.L.; Yu, D.L. Monitoring and evaluating spatial variability of soil salinity in dry and wet seasons in the Werigan-Kuqa Oasis, China, using remote sensing and electromagnetic induction instruments. *Geoderma* **2014**, *235*, 316–322. [CrossRef]
41. Jialaliding, A.; Tursun, T.; Mamat, R. Research on Water and Soil Resources in Weiganhe River Basin of Xinjiang. *Hubei Agric. Sci.* **2013**, *52*, 2532–2535.
42. Cao, L.; Ding, J.; Yu, H. Relationship between multi-scale landscape pattern and salinity in Weigan and Kuqa rivers delta oasis. *Trans. Chin. Soc. Agric. Eng.* **2016**, *32*, 101–110.
43. Kang, X.; Wang, X.; Chai, Z. Land Use/Cover Changes and Influencing Factors in Delta Oasis of Weigan-Kuqa River During Last 25 Years. *Bull. Soil Water Conserv.* **2016**, *36*, 333–339.
44. Litan, S.U.; Song, Y.; Zhang, Z. Study on the Spatio-temporal Variation of Groundwater Salt Content in Xinjiang Weigan Catchment. *Acta Geogr. Sin.* **2003**, *58*, 854–860.
45. Moeck, C.; Brunner, P.; Hunkeler, D. The influence of model structure on groundwater recharge rates in climate-change impact studies. *Hydrogeol. J.* **2016**, *24*, 1171–1184. [CrossRef]
46. Cinnirella, S.; Buttafuoco, G.; Pirrone, N. Stochastic analysis to assess the spatial distribution of groundwater nitrate concentrations in the Po catchment (Italy). *Environ. Pollut.* **2005**, *133*, 569–580. [CrossRef]
47. Boken, V.K.; Hoogenboom, G.; Hook, J.E.; Thomas, D.L.; Guerra, L.C.; Harrison, K.A. Agricultural water use estimation using geospatial modeling and a geographic information system. *Agric. Water Manag.* **2004**, *67*, 185–199. [CrossRef]
48. Sun, Y.; Kang, S.Z.; Li, F.S.; Zhang, L. Comparison of interpolation methods for depth to groundwater and its temporal and spatial variations in the Minqin oasis of northwest China. *Environ. Modell. Softw.* **2009**, *24*, 1163–1170. [CrossRef]
49. Yao, L.Q.; Huo, Z.L.; Feng, S.Y.; Mao, X.M.; Kang, S.Z.; Chen, J.; Xu, J.J.; Steenhuis, T.S. Evaluation of spatial interpolation methods for groundwater level in an arid inland oasis, northwest China. *Environ. Earth Sci.* **2014**, *71*, 1911–1924. [CrossRef]
50. Elbasiouny, H.; Abowaly, M.; Abu Alkheir, A.; Gad, A. Spatial variation of soil carbon and nitrogen pools by using ordinary Kriging method in an area of north Nile Delta, Egypt. *Catena* **2014**, *113*, 70–78. [CrossRef]
51. Phachomphon, K.; Dlamini, P.; Chaplot, V. Estimating carbon stocks at a regional level using soil information and easily accessible auxiliary variables. *Geoderma* **2010**, *155*, 372–380. [CrossRef]
52. Huang, Y.J.; Ye, H.C.; Zhang, L.P.; Zhang, S.W.; Shen, C.Y.; Li, Z.; Huang, Y.F. Prediction of Soil Organic Matter Using Ordinary Kriging Combined with the Clustering of Self-organizing Map: A Case Study in Pinggu District, Beijing, China. *Soil Sci.* **2017**, *182*, 52–62. [CrossRef]
53. Mueller, T.G.; Pusuluri, N.B.; Mathias, K.K.; Cornelius, P.L.; Barnhisel, R.I.; Shearer, S.A. Map quality for ordinary kriging and inverse distance weighted interpolation. *Soil Sci. Soc. Am. J.* **2004**, *68*, 2042–2047. [CrossRef]
54. Bagan, H.; Yamagata, Y. Landsat analysis of urban growth: How Tokyo became the world's largest megacity during the last 40 years. *Remote Sens. Environ.* **2012**, *127*, 210–222. [CrossRef]
55. Boots, B. Geographically weighted regression: The analysis of spatially varying relationships. *Int. J. Geogr. Inf. Sci.* **2003**, *17*, 717–719.
56. Georganos, S.; Abdi, A.M.; Tenenbaum, D.E.; Kalogirou, S. Examining the NDVI-rainfall relationship in the semi-arid Sahel using geographically weighted regression. *J. Arid Environ.* **2017**, *146*, 64–74. [CrossRef]
57. Harris, P.; Fotheringham, A.S.; Crespo, R.; Charlton, M. The Use of Geographically Weighted Regression for Spatial Prediction: An Evaluation of Models Using Simulated Data Sets. *Math. Geosci.* **2011**, *43*, 399. [CrossRef]
58. Shabiti, M.; Jiang-Ling, H.U. Effects of Groundwater Characteristics on Vegetation in the Oasis on the Ugan-Kuqa River Delta, Xinjiang Region, China. *J. Glaciol. Geocryol.* **2010**, *32*, 422–428.
59. Zhang, X.; Zhang, L.; He, C.; Li, J.; Jiang, Y.; Ma, L. Quantifying the impacts of land use/land cover change on groundwater depletion in Northwestern China—A case study of the Dunhuang oasis. *Agric. Water Manag.* **2014**, *146*, 270–279. [CrossRef]

60. Pulido-Velazquez, M.; Pena-Haro, S.; Garcia-Prats, A.; Mocholi-Almudever, A.F.; Henriquez-Dole, L.; Macian-Sorribes, H.; Lopez-Nicolas, A. Integrated assessment of the impact of climate and land use changes on groundwater quantity and quality in the Mancha Oriental system (Spain). *Hydrol. Earth Syst. Sci.* **2015**, *19*, 1677–1693. [CrossRef]
61. Xu, Y.Q.; Mo, X.G.; Cai, Y.L.; Li, X.B. Analysis on groundwater table drawdown by land use and the quest for sustainable water use in the Hebei Plain in China. *Agric. Water Manag.* **2005**, *75*, 38–53. [CrossRef]
62. Kettle, N.; Harrington, L.; Harrington, J. Groundwater depletion and agricultural land use change in the high plains: A case study from Wichita County, Kansas. *Prof. Geogr.* **2007**, *59*, 221–235. [CrossRef]
63. Sabit, M.; Yusuf, N.; Nasierding, N. Supply and demand analysis on water resources in Weigan river-Kuqa river delta oasis, Xinjiang. *J. Arid Land Resour. Environ.* **2010**, *24*, 145–149.
64. Huang, F.; Qiao, X.N.; Tang, H. Temporal and spatial dynamic changes of land use and ecosystem service value in the Weigan River Basin in recent 20 years. *Agric. Res. Arid Areas.* **2013**, *31*, 213–223.
65. Mizutani, Y.; Uesugi, Y.; Kitagawa, T. Characteristics of temporal and spatial dynamic changes of land use and their relationship with regional development—A case study in the Weigan River Basin. *Agric. Res. Arid Areas.* **2012**, *38*, 127–135.
66. Wang, D.D.; Yu, Z.; Cheng, M.; Zhao, C.Y.; Ding, J.L.; Zhang, X.L. Characteristics of soil salinity under different land use types in Weigan River Oasis. *Arid Land Geogr.* **2018**, *41*, 349–357.
67. Wang, H.W.; Ding, J.L.; Xie, X. Spatial Quantitative Research of Ecosystem Service Value Based on Land Use in the Delta Oasis of Weigan and Kuqa River. *Xinjiang Agric. Sci.* **2014**, *10*, 1887–1892.